EXPLOSIVE PULSED POWER: AN ENABLING TECHNOLOGY

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ABSTRACT

The modern army is currently striving to make their weapon systems smaller, lighter, and cheaper and at the same time more powerful. One of the enabling technologies that permit this is Explosive Pulsed Power (EPP). Explosive Pulsed Power consists of those devices that convert the chemical energy in explosives into electrical energy. In 2004, a series of Army Small Business Innovative Research (SBIR) Programs were initiated to develop several types of very compact EPP Generators. Based on these recent efforts, we now have a better understanding of the weaknesses and strengths of these small generators. As a result, we can now build reliable generators that provide consistent output currents and voltages. In this paper, a brief introduction to these generators will be given along some of the most recent advances in our understanding of them. This paper will only report on advances made by Army and Navy researchers and that of their contractors. A description of an explosive driven high power microwave test bed built at Texas Tech will be presented. A brief description of some applications of EPP will also be presented.

1. INTRODUCTION

Traditional power supplies can not meet the volume and mass constraints imposed by many current platforms. In order to meet these imposing requirements, an enabling technology is required. It was realized in the 1950s that one way to achieve these requirements was to use Explosive Pulsed Power (EPP). Over the years, a number of explosive pulsed power devices were developed. In recent years, there have been significant improvements in EPP primarily due to the development of new materials and to consistently funded experimental programs. Therefore, these explosive-driven systems are now being considered for a number of new applications including directed energy, powering special test equipment at remote test sites, rapid charging of capacitors, mine detection, propulsion, lightning and electromagnetic pulse (EMP) simulators, electromagnetic launchers, mineral and oil exploration, and blasting operations at mines and quarries.

Of the 5 general classes of EPPs [1], only three will be considered in this paper and they include:

- Magnetic Flux Compression Generators (FCGs).
- Ferroelectric Generators (FEGs).
- Ferromagnetic Generators (FMGs).

These are the generators that appear to have practical near term applications [1]. The magnetic flux compressing generator (FCG) is a high energy source, the ferroelectric generator (FEG) is a high voltage source, and the ferromagnetic generator (FMG) can be either a high voltage or a high current source depending on how it is built. The FEG and FMG are relatively low energy sources.

2. WHAT IS EXPLOSIVE PULSED POWER?

Explosive pulsed power evolved out of the nuclear weapon programs in the United States, the United Kingdom, and the Soviet Union. These countries were looking for methods to solve several technical problems including driving fusion reactions without using a fission primer and driving detonator arrays and neutron sources.

Explosive pulsed power devices fall into one of two broad categories:

- Devices that convert the chemical energy of explosives into electrical energy by driving a conducting medium through a magnetic or an electric field. This is accomplished by transforming the chemical energy of the high explosives into the kinetic energy of a moving conducting material. This moving conduction boundary distorts or does work on the magnetic field that results in the conversion of its kinetic energy into electrical energy. We will call this type of generator *field interaction generators*.
- Devices that use the shock waves generated by high explosives to induce a phase change in a material that stores energy in the form of electric or magnetic fields and cause this stored energy to be released as electrical energy. We will call this type of generator *phase transition generators*.

3. GENERATOR DESCRIPTON

The flux compression generator, ferroelectric generator, and ferromagnetic generator each operate in their own unique way.

- Flux Compression Generators (FCGs) use the chemical energy from high explosives to accelerate a metallic conductor, called the *armature* that traps and compresses a magnetic field initially created by a seed energy source such as a capacitor bank, battery, or another pulsed EEP generator. The

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accelerating armature compresses the seed magnetic field trapped within a conducting shell that is comprised of the armature, a stationary conductor called the *stator*, and end *glide planes*. When the armature makes electrical contact with the input glide plane, the initial magnetic flux from the seed source is trapped, the seed circuit is disconnected from the generator, and the stator-armature-load circuit is closed. This process is called *crowbarring*. When the armature makes contact with the stator, a moving electrically conducting *contact point* is established. If the FCG is a helical generator, the contact point propagates along the wire of the helical coil (stator) as the expanding conically shaped armature propagates along the axis of the generator. Compression of the trapped magnetic flux multiplies the initial seed current flowing in the stator. This amplified current is then delivered to a load either directly or through a power conditioning circuit. The energy density of an FCG; i.e., the ratio of the electrical energy delivered to the load and the FCG volume, is typically a few Joules/cubic centimeter. Note, however, that this number is critically dependent on the generator design and the load itself. In general, the smaller the load inductance, the higher the energy output. However, if the load inductance is too small, then the FCG can not efficiently drive such a load, which includes narrow band microwave sources or antennas.

- Ferroelectric Generators (FEGs) use the chemical energy from high explosives to generate a shock wave. Ferroelectric materials store electrical energy when they are externally poled by an electric field. When a shock wave passes through the poled material, it causes a phase change in the crystalline structure. This phase change either depoles the material or causes the material to transition from one crystalline state to another and releases the stored electrical charge (or energy) via electrodes attached to the ferroelectric element to an external circuit. This released electric charge (or energy) is then delivered to a load via a power conditioning circuit. This type of generator can be used to deliver high voltages to high impedance loads and is suitable for the direct drive of radiating circuits.
- Ferromagnetic Generators (FMGs) use the chemical energy from high explosives to generate a shock wave to de-magnetize a permanent magnet. Ferromagnetic materials store energy in the form of a magnetic field when they are externally magnetized. When a shock wave passes through the ferromagnetic material, it destroys the magnet and the magnetic domains within the magnet. This changing magnetic field induces a current in a pickup coil around the magnet, which is then delivered to a load via a power conditioning circuit. This type of generator can be used to deliver large currents to low impedance loads and can generate higher voltages for moderate impedance loads.

The FCG is a field interaction type generator, while the FEG and FMG are phase transition type generators.

4. RECENT ADVANCES IN EPP GENERATORS

As noted earlier, the development of new types of materials and sustained experimental programs have led to significant improvements in our understanding of EPPs and, in some cases, breakthroughs in improving their performance.

4.1 Flux Compression Generators

There are several different variants of small FCGs, but they all operate on the same basic principle of compressing a magnetic field in an enclosed conducting volume or magnetic field flux trap. They differ primarily in the shape of their conductors, which is limited by the types of explosive initiation systems that are available. In other words, practical initiation systems may not be possible for some geometric configurations.

In recent years, there have been two major advances in our understanding of the processes that take place in helical FCGs (Fig. 1). First is the work done by Baird [2], who conducted a detailed study of the fracture mechanics of the armature under shock loading. Second is that of Kiuttu [3, 4], who developed a resistance model for the contact point between the stator and armature. In addition, there has been recent work done by Gilev [5], Hemmert [6], and Freeman [7] on dielectric filled helical generators (SWGs), which may offer some advantages over classical helical FCGs. The SWG will not be discussed in this paper.

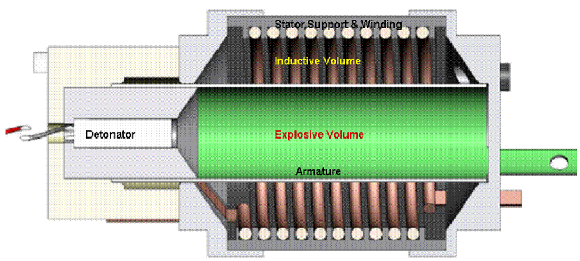

Fig. 1 Helical Flux Compression Generator

4.1.1 Armature Studies

While studying the propagation of the armature of an end fired helical FCG, Baird [2] observed the formation of a new type of fracture in expanding armatures and was able to answer questions about the impact of armature defects and voids in the explosives on generator operation. Based on his studies, he was able to explain why simultaneously initiated radially driven

armatures are different from end fired axially propagating expanding armatures in conventional helical FCGs and, thus, how to deal with this difference to offset some of their more major problems.

The main areas that Baird focused his research on were the impact of the following on generator losses:

- Expansion and fracturing of the armature.
- Armature defects.
- Explosive packing and voids.

The armatures used in this study were made of copper or aluminum. The oxygen-free high conductivity copper cylinders were annealed to the soft state prior to testing and the aluminum cylinders were tested in both the hard and soft states.

Examination of the high-speed photography of the expanding armatures revealed a previously unknown cracking on the outer surface of the armatures. These cracks appeared in both types of metals, no matter their annealed state. These longitudinal cracks began on the surface of the armature at the detonator end of the cylinder and always stopped their extension at identical distances along the cylinders. Since the armature is part of the generator's electric circuit and since the electric currents flow in a circumferential direction along its outer surface, it was thought that this might be one of the generator's loss mechanisms. The formation of cracks would introduce a loss of containment and result in magnetic flux losses. This cracking could also lead to arcing between the armature and the stator. The arcing could cause the stator insulation to break down before the sliding contact reaches that location, resulting in a high resistance contact between the armature and stator and the potential loss of magnetic confinement. That is, the arcing causes the current flowing from the armature to the stator to jump ahead of the sliding contact, which is now no longer the current path. The magnetic flux is now trapped in the region between the sliding contact and the arcing and is lost to the compression process.

Metals tend to break when stressed beyond their strength limitations or when subjected to high strain rates. In the case of metal cylinders, this limit is reached when it is expanded to more than twice its original diameter. It has long been known to researchers that the initiated end of the armature needed to be extended at least two diameters beyond the end of the stator for the generator to operate properly, but the reason was not well understood. Explosive expansion produces circumferential strains that can cause cracks that extend along the entire length of the armature. However, Baird found that fracturing occurred much sooner than expected. In addition, he found that the fractures did not extend the length of the armature, as expected if they were purely the result of explosive expansion. This longitudinal fracturing only occurred within two diameters of the initiated end of the armature. Also, this fracturing was occurring at much lower armature diameter expansion ratios than expected. Finally, normal explosive expansion fracturing begins on the inner surface, while the observed longitudinal fracturing occurs on the outer surface of the cylinder. Therefore, it was concluded that this unusual longitudinal fracturing was not due to explosive expansion, but rather some other effect; namely, shock dynamics within the armature.

For several decades there was an ongoing debate about the effects of armature surface defects on generator performance. The same cylinders used in the armature fracture study were also used in an armature defect study [8, 9]. Tests were conducted using copper and aluminum armatures that had been polished and those that had rough finishes. It was found that the surface finish had little or no effect on the armature's expanding surface.

Since the C-4 explosives were hand packed in the above experiments, there was concern about the uniformity of the explosive charge and the existence of voids. The explosive was hand loaded by using two methods. The first was to roll it into balls and then tamp them into the armature. This technique was thought to introduce cross-sectional voids and low-density regions within the charge. The second method was to form 2 cm disks and to push them into the armature. This method was thought to introduce mold line type voids. To understand the impact of voids on generator operation, 4 mm diameter spherical glass beads were introduced at various points within the explosive charge to simulate voids. In one set of experiments, the beads were placed along the charge-armature interface and in another set they were in the body of the charge. The tests established that concerns about hand-packing were unfounded, as long as care was exercised to ensure that portions of explosive charge were knitted closely with previously loaded portions to prevent armature surface irregularities during expansion and that the only voids that appeared to effect armature expansion were those located at or near the explosive-armature interface.

In summary, only detonation wave phenomenon, such as transmission, reflection, refraction, and trailing rarefactions, are capable of producing incipient fractures at the locations and times where the cracking began on the outer surface of the armatures. The longitudinal fractures are caused by shock waves, not the expansion due to the detonation. The expansion only opens the fractures once they are initiated. In addition, it was demonstrated that surface finish and voids have minimal impact on armature expansion.

4.1.2 Kiuttu Contact Point Resistance Model

One important characteristic of the helical FCG is its time dependent electrical resistance. While developing a contact resistance model for the helical FCG, Kiuttu found an explanation for why small FCGs do not work as well as larger FCGs.

Kiuttu and Chase [3, 4] developed a resistance model, which includes diffusion and proximity effects, for the armature-stator contact point. In order to develop this model, they developed an analytical expression that estimates the rate of magnetic field diffusion in the vicinity of the contact point. When converted to a flux loss rate, they found that it usually scales nonlinearly with the instantaneous current and that the resulting effective resistance is proportional to the square root of the current. Further, they found that the contact resistance generally increases throughout generator operation, even though the overall helical FCG resistance decreases as the generator length decreases. Finally, they found that the contact resistance usually dominates towards the end of generator operation and ultimately limits the gain of many helical generators, especially the smaller systems.

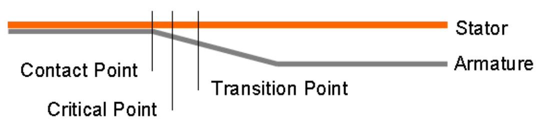

Fig. 2 Kiuttu and Chase divide the helical FCG into sections separated by two points: Critical Point, where the local Magnetic Reynolds Number is unity, and the Transition Point, where the wire-to-wire proximity effect is equal to the wire-to-armature proximity effect [3, 4]

Kiuttu and Chase postulated that there are there are three distinct regions (Fig. 2) in the vicinity where the armature makes contact with the stator. The first is the *Transition Point*. In the region downstream from this point, diffusion of flux into the stator is governed by the concentration of the field on the underside of the stator due to the wire-to-wire proximity effect. The P*roximity Effect* is where the presence of the wires of the stator alters the magnetic field and current density distributions that initially existed before the arrival of the contact point. These non-uniform magnetic field distributions around the wire increase the resistance. The second point is the *Critical Point*, which is the point ahead of the contact point that defines the region where most of the flux behind it diffuses into the conductors and most of the flux ahead of it is advected ahead towards the load. They further postulated that if the flux per unit length in the armature-stator gap at the critical point could be determined and that if it is multiplied by the critical point velocity, then the effective voltage and, thus, the resistance across the generator at that point can be found. The three parameters that must be found are the location of the critical point, its velocity, and the flux per unit length at that point.

To find the location of the critical point, they introduced the Magnetic Reynolds Number. It is a dimensionless quantity that relates the relative importance of flux advection to that of diffusion and is defined to be the ratio of the time to move flux over a given distance in vacuum to the time it takes for it to diffuse the same distance into a resistive medium. In other words, the critical point is the point at which the rate of flux diffusion into the conductor just equals the rate at which the flux is pushed ahead of the armature and its Magnetic Reynolds Number is defined to be equal to one.

Since the distances between these three points are very small, there are strong armature-stator proximity effects that make the surface fields very strong, thus causing nonlinear diffusion. The contact point resistance is nonlinear and scales as the square root of the current. It depends weakly on the properties of the materials used to construct the generator and the armature expansion angle. This model appears to give good results when applied to small and medium size simple helical FCGs and has been incorporated into the CAGEN 1 1/2 –D modeling code for helical FCGs.

4.2 Ferroelectric Generator

The first paper describing explosive driven FEGs was published by Nielsen [10] in 1957. Throughout the 1960s and 1970s, FEGs were intensely studied at Sandia National Laboratory and the Naval Surface Weapons Center, but research on these generators declined until it was revived in the late 1990s at Sandia [11]. In the late 1990s, Texas Tech University [12] began a systematic investigation of FEGs. This work was continued by Loki, Inc. [13] and HEM Technologies [14]. Loki has developed FEGs (Fig. 3) to the point that they can reliably generate consistent voltages in excess of 100 kV from a device with a diameter less than 50 mm and a length less than 90 mm. One of their most significant findings is that these generators can generate multiple pulses despite being a single shot device.

Some of the recent advances in FEGs are the identification of

- New ferroelectric materials with higher energy storage densities and higher electric breakdown thresholds that significantly increases the output voltage of the FEG.
- New potting materials that yield good electrical, mechanical, and shock properties.
- Improved power conditioning techniques that yield optimal output voltages and provide better impedance matching with a variety of loads.

  The most significant improvement in FEGs is due to advances in ferroelectric ceramics. Texas Tech and Loki used standard commercial PZT in their FEGs, but based on work done by Sandia National Laboratory; it was obvious that there were better materials available, in particular PZT 95/5. Since PZT 95/5 was not available to researchers

outside of Sandia, TRS Technologies, under an SBIR program, managed to develop and refine a process for producing sufficient quantities of PZT 95/5 for testing. HEM Technologies, working with TRS, proved that TRS's PZT 95/5 material clearly outperforms the more traditional PZTs (EC-64 and TRS100) in charge release, while maintaining a similar dielectric strength. Comparing the TRS PZT 95/5 to that produced by Sandia and reported on the literature indicates that the TRS PZT 95/5 material outperforms that produced by Sandia. However, without samples of both to test in identical setups, it is difficult to make a conclusive statement about the relative performance of the two formulations.

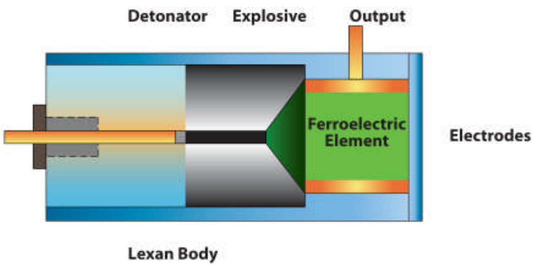

Fig. 3 Ferroelectric Generator developed by Loki Inc.

From their systematic study of FEGs, Loki observed the following trends:

- The output voltage produced by an FEG is directly proportional to the number of PZT elements used.
- For FEGs operating with high resistive loads, the amplitude and Full Width Half Maximum (FWHM) of the voltage pulse produced by FEGs are highly reproducible and increases as the thickness of the PZT element increases. In addition, increasing PZT thickness increases the energy produced by the FEG, but reduces the specific energy density stored in the PZT.
- For FEGs operating with resistive loads, the amplitude of the output voltage increases exponentially as the resistance increases. However, the amplitude of the current pulse decreases as the resistance increases. The power and energy transferred to the load increases up to a certain load resistance, after which it decreases.
- For FEGs operating with capacitive loads, the amplitude of the voltage pulse decreases as the capacitance increases. However, the electric charge transferred to the load increases as the capacitance increases. The energy transferred to the load increases up to a certain load capacitance, after which it decreases.
- Certain ferroelectric and potting materials and certain ferroelectric element shapes are better than others for yielding high output voltages. As an example, Loki shot single element generators with rectangular shaped EC-64 and PZT 95/5 elements and one with a cylindrically shaped PZT 95/5 element. The latter provided significantly higher voltages.

In summary, it is now possible to produce FEGs that are highly reliable and that can consistently generate high voltages of roughly the same magnitude. In addition, it has been found that FEGs work well with a variety of loads and power conditioning circuits.

4.3 Ferromagnetic Generators

The first paper describing explosive driven FMGs was published by Nielsen [10] in 1957. In the late 1990s, Texas Tech University [15] began a systematic investigation of FMGs. This effort was later continued by Loki, Inc. [16].

Ferromagnetic generators may be classified as being either high current (kA's) or high voltage (kV's) sources. Increasing the number of turns in the output coil of the FMG increases its output voltage. Thus, a single turn FEG is a high current source, while a multi-turn FMG is a high voltage source.

Unlike the FEGs and FCGs, the FMG (Fig. 4) is not directly part of the circuit. Thus, one advantage of the shock wave FMG over the other types of explosive driven power sources is that the pulse generating circuit is not electrically connected directly to the ferromagnetic elements. The ferromagnet is electrically insulated from the pulse generating coil, so there is only transformer coupling between the ferromagnet and the pulse generating coil. Therefore, the pulse generating coil of the FMG is not subjected to explosive shock during the demagnetization process and its electrical parameters are not affected by the shock until after FMG operation is complete. Another advantage is the relative long pulse they produce, making them good seed sources for FCGs.

From their systematic study of FMGs, Loki observed the following trends:

- As the number of turns in the pulse generating coil, the peak amplitude of the voltage pulse increases proportionally.
- As the number of magnets in the FMG increases, the peak amplitude of the voltage pulse increases.
- It has been experimentally determined that FMGs reliably generate electrical pulses with a pulse length of about 50 μs which is sufficient time for charging capacitor banks and seeding FCGs.

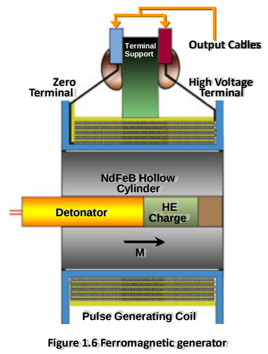

Fig. 4 Ferromagnetic Generator developed by Loki Inc.

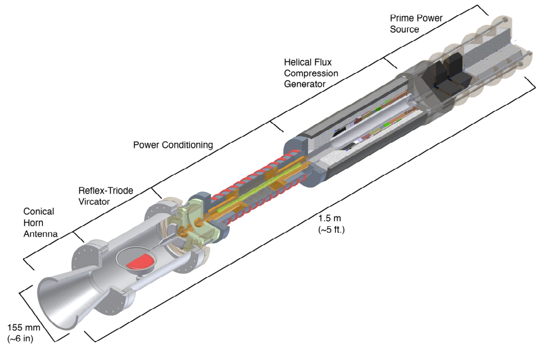

Fig. 5 Texas Tech explosive driven HPM test bed.

Several FMG designs have been built and tested and the optimal design is one where a hole is drilled into a cylindrical magnet and the explosive charge is placed within the hole.. The shock wave moves perpendicular to the magnetic field vector. FMGs with magnets having a volume of 50 cm^3 are capable of generating several tens of kiloamps.

5 APPLICATIONS

5.1 Explosive-Driven HPM Test Bed

Texas Tech University is developing a compact, explosive-driven high power microwave (HPM) test bed. The major design constraints [17, 18] were that the system had to

- Be completely self-contained; i.e., no external power source,
- Fit into a volume with a diameter no greater than 15 cm and a length no greater than 1.5 m, and
- Radiate energy.

The primary objectives were to develop and optimize the various components of the system, study the issues associated with system integration, and train students to work with EPP. Of these three objectives the training of students is the most important. Explosive pulsed power is a multidisciplinary subject requiring training in high explosives, high voltage engineering, general electrical engineering, material science, vacuum engineering, and so on.

The major components of the test bed are shown in Fig. 5. As can be seen, it consists of a prime power or seed source for the flux compression generator, a helical FCG, a power conditioning module, a microwave source, and an antenna.

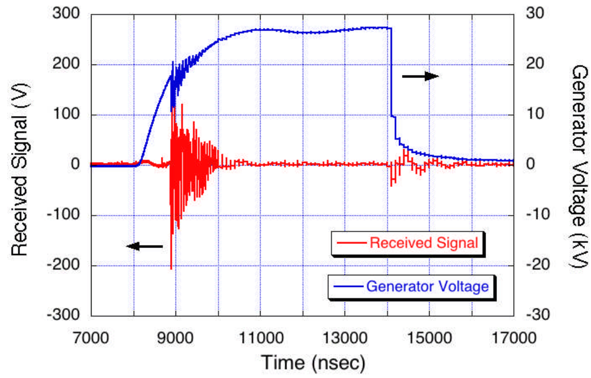

Fig. 6 Voltage generated by FEG and signal received by antenna at 3 m.

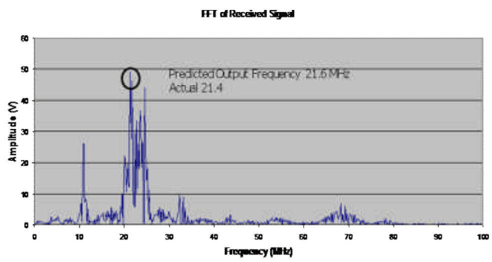

Fig. 7 FFT of the received signal at 3 m.

5.2 Experimental Observation of RF Radiation Generated by an FEG Driven Antenna

In 2005, the Naval Research Laboratory and Loki Inc. [19] conducted a series of tests in which they used a FEG to drive an antenna through a simple pulse forming network. They conducted three test shots using the same dipole antenna and pulse forming network and FEGs that had identical or similar physical configurations. A similar receiving dipole antenna was placed approximately 3 m from the transmitting antenna. The received waveforms were recorded along with the voltage pulse (Fig. 6) delivered by the FEG to the pulse forming network.

Using the peak voltages picked up by the receive antenna, the peak power density at the antennas was 1.64 W/cm^2 and the Effective Radiated Power (ERP) at the source antenna was 2 MW, assuming a near unity gain of the receiving antenna. The FEG generated about 2.4 MW.

A Fast Fourier Transform (FFT) (Fig. 7) revealed that the spectrum of the RF bursts was concentrated between 18 and 26 MHz, with largest signal at 21.4

MHz, which is in good agreement with the predicted value of 21.67 MHz.

5.3 Powering Lasers with FCGs

Flux compression generators have been used to drive high power lasers including neodymium (Nd) glass and iodine lasers. Jones, Fowler, and Ware [20] used a plate FCG to drive an exploding foil film to pump an iodine laser. Pavlovskii et al. [21] used FCGs to charge inductive stores, which, in turn, delivered electrical pulses with the proper waveform to the pumping lamps of the laser.

5.4 Powering HPM Sources with FCGs

Flux Compression generators have been used to drive several different types of HPM sources including magnetrons, Vircators, Magnetically Insulated Line Oscillators (MILOs), and Backward Wave Oscillators (BWOs). In the mid 1980s, Freeman et al. [22] used a fast plate FCG to drive a Vircator. The FCG was connected through an air-core transformer to achieve impedance matching to the diode of the Vircator and to increase the output voltage of the FCG to meet the requirements of the Vircator. Radiation was detected in the L-, S-, and X-bands of the spectrum.

5.5 Space-Based Plasma Generators – Project Birdseed

In 1969, Los Alamos National Laboratory and Sandia National Laboratory installed a plasma gun powered by two FCGs into a rocket and launched it into the ionosphere (an altitude of ~ 200 km) [23]. They injected a neon plasma into the ionosphere. There was concern as to whether or not the system would survive the four minute trip from launch to the ionosphere. However, it was determined that all three launches of this system were successful.

Fig. 8 Left to Right: 42 mm, 125 mm, 105 mm, and 122 mm EMAs.

5.6 Electromagnetic Ammunition

Beginning in 1994 [24], A.B. Prishchepenko published a series of papers on devices he calls *Electromagnetic Ammunition*. Electromagnetic ammunition consists of an EEP source and a capacitive load. The purpose of this ammunition was to upset and/or destroy electronics. These munitions [25] ranged in size from 42 mm to 125 mm (Fig. 8). The 42 mm round used an FEG as the power supply and the 105, 122, and 125 mm rounds used an FCG as the power supply

CONCLUSIONS

Our improved understanding of the failure mechanisms observed in FCGs has provided us with clues on how to improve their performance. Researchers now understand why medium size generators work better than small FCGs and why completely new designs, such as the Shock Wave Generator (SWG), must be developed.

Improvements in ferroelectric materials and potting materials have allowed us to build FEGs with diameters as small as 40 mm that can consistently generate open circuit voltages in excess of 100 kV. These FEGs have been used for a number of applications including charging capacitor banks and vector inversion generators and driving antennas to produce radiated energy.

Ferromagnetic generators with diameters less than 50 mm have been successfully used to seed FCGs. These generators have proven to be reliable and capable of providing highly repeatable pulses. This enables us to build very compact completely autonomous EEP systems based on FCGs to drive a variety of payloads.

It has been demonstrated that FCGs can drive high power microwave sources and that FEGs can direct drive antennas to produce radiated signals.

Finally, Texas Tech has created a test bed that incorporates all the major components of a self-contained explosive driven HPM system. This will enable them and other researchers to test new components, address integrations issues, and train students in the use of high explosives, high voltage engineering, and HPM.

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